

FORM PTO-1390 (Modified) (REV 7-95)		U.S. DEPARTMENT OF COMMERCE PATENT AND TRADEMARK OFFICE		ATTORNEY'S DOCKET NUMBER 200351US2PCT	
TRANSMITTAL LETTER TO THE UNITED STATES DESIGNATED/ELECTED OFFICE (DO/EO/US) CONCERNING A FILING UNDER 35 U.S.C. 371				U.S. APPLICATION NO. (IF KNOWN, SEE 37 CFR <div style="font-size: 1.2em; font-weight: bold; text-align: center;">09/719158</div>	
INTERNATIONAL APPLICATION NO. PCT/JP99/06244		INTERNATIONAL FILING DATE 10 November 1999		PRIORITY DATE CLAIMED 12 April 1999	
TITLE OF INVENTION PHOTON NUMBER STATE GENERATING APPARATUS					
APPLICANT(S) FOR DO/EO/US Shigeki TAKEUCHI					
Applicant herewith submits to the United States Designated/Elected Office (DO/EO/US) the following items and other information:					
<ol style="list-style-type: none"> 1. <input checked="" type="checkbox"/> This is a FIRST submission of items concerning a filing under 35 U.S.C. 371. 2. <input type="checkbox"/> This is a SECOND or SUBSEQUENT submission of items concerning a filing under 35 U.S.C. 371. 3. <input checked="" type="checkbox"/> This is an express request to begin national examination procedures (35 U.S.C. 371(f)) at any time rather than delay examination until the expiration of the applicable time limit set in 35 U.S.C. 371(b) and PCT Articles 22 and 39(1). 4. <input type="checkbox"/> A proper Demand for International Preliminary Examination was made by the 19th month from the earliest claimed priority date. 5. <input checked="" type="checkbox"/> A copy of the International Application as filed (35 U.S.C. 371 (c) (2)) <ol style="list-style-type: none"> a. <input type="checkbox"/> is transmitted herewith (required only if not transmitted by the International Bureau). b. <input checked="" type="checkbox"/> has been transmitted by the International Bureau. c. <input type="checkbox"/> is not required, as the application was filed in the United States Receiving Office (RO/US). 6. <input checked="" type="checkbox"/> A translation of the International Application into English (35 U.S.C. 371(c)(2)). 7. <input checked="" type="checkbox"/> A copy of the International Search Report (PCT/ISA/210). 8. <input checked="" type="checkbox"/> Amendments to the claims of the International Application under PCT Article 19 (35 U.S.C. 371 (c)(3)) <ol style="list-style-type: none"> a. <input type="checkbox"/> are transmitted herewith (required only if not transmitted by the International Bureau). b. <input type="checkbox"/> have been transmitted by the International Bureau. c. <input type="checkbox"/> have not been made; however, the time limit for making such amendments has NOT expired. d. <input checked="" type="checkbox"/> have not been made and will not be made. 9. <input type="checkbox"/> A translation of the amendments to the claims under PCT Article 19 (35 U.S.C. 371(c)(3)). 10. <input checked="" type="checkbox"/> An oath or declaration of the inventor(s) (35 U.S.C. 371 (c)(4)). 11. <input type="checkbox"/> A copy of the International Preliminary Examination Report (PCT/IPEA/409). 12. <input type="checkbox"/> A translation of the annexes to the International Preliminary Examination Report under PCT Article 36 (35 U.S.C. 371 (c)(5)). 					
Items 13 to 18 below concern document(s) or information included:					
<ol style="list-style-type: none"> 13. <input type="checkbox"/> An Information Disclosure Statement under 37 CFR 1.97 and 1.98. 14. <input type="checkbox"/> An assignment document for recording. A separate cover sheet in compliance with 37 CFR 3.28 and 3.31 is included. 15. <input type="checkbox"/> A FIRST preliminary amendment. A SECOND or SUBSEQUENT preliminary amendment. 16. <input type="checkbox"/> A substitute specification. 17. <input type="checkbox"/> A change of power of attorney and/or address letter. 18. <input type="checkbox"/> Certificate of Mailing by Express Mail 19. <input checked="" type="checkbox"/> Other items or information: 					
Request for Consideration of Documents Cited in International Search Report Notice of Priority PCT/IB/304 PCT/IB/308 Drawings (11 sheets)					


U.S. APPLICATION NO. (IF KNOWN, SEE 37 CFR 09/7719158)		INTERNATIONAL APPLICATION NO. PCT/JP99/06244		ATTORNEY'S DOCKET NUMBER 200351US2PCT	
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20. The following fees are submitted..				CALCULATIONS PTO USE ONLY	
BASIC NATIONAL FEE (37 CFR 1.492 (a) (1) - (5)) : <input checked="" type="checkbox"/> Search Report has been prepared by the EPO or JPO \$860.00 <input type="checkbox"/> International preliminary examination fee paid to USPTO (37 CFR 1.482) \$690.00 <input type="checkbox"/> No international preliminary examination fee paid to USPTO (37 CFR 1.482) but international search fee paid to USPTO (37 CFR 1.445(a)(2)) \$710.00 <input type="checkbox"/> Neither international preliminary examination fee (37 CFR 1.482) nor international search fee (37 CFR 1.445(a)(2)) paid to USPTO \$1000.00 <input type="checkbox"/> International preliminary examination fee paid to USPTO (37 CFR 1.482) and all claims satisfied provisions of PCT Article 33(2)-(4) \$100.00					
ENTER APPROPRIATE BASIC FEE AMOUNT =				\$860.00	
Surcharge of \$130.00 for furnishing the oath or declaration later than months from the earliest claimed priority date (37 CFR 1.492 (e)). <input type="checkbox"/> 20 <input type="checkbox"/> 30				\$0.00	
CLAIMS	NUMBER FILED	NUMBER EXTRA	RATE		
Total claims	14 - 20 =	0	x \$18.00	\$0.00	
Independent claims	1 - 3 =	0	x \$80.00	\$0.00	
Multiple Dependent Claims (check if applicable). <input type="checkbox"/>				\$0.00	
TOTAL OF ABOVE CALCULATIONS =				\$860.00	
Reduction of 1/2 for filing by small entity, if applicable. Verified Small Entity Statement must also be filed (Note 37 CFR 1.9, 1.27, 1.28) (check if applicable). <input type="checkbox"/>				\$0.00	
SUBTOTAL =				\$860.00	
Processing fee of \$130.00 for furnishing the English translation later than months from the earliest claimed priority date (37 CFR 1.492 (f)). <input type="checkbox"/> 20 <input type="checkbox"/> 30 +				\$0.00	
TOTAL NATIONAL FEE =				\$860.00	
Fee for recording the enclosed assignment (37 CFR 1.21(h)). The assignment must be accompanied by an appropriate cover sheet (37 CFR 3.28, 3.31) (check if applicable). <input type="checkbox"/>				\$0.00	
TOTAL FEES ENCLOSED =				\$860.00	
				Amount to be: refunded \$	
				charged \$	

<input checked="" type="checkbox"/> A check in the amount of \$860.00 to cover the above fees is enclosed. <input type="checkbox"/> Please charge my Deposit Account No. _____ in the amount of _____ to cover the above fees. A duplicate copy of this sheet is enclosed.	
<input checked="" type="checkbox"/> The Commissioner is hereby authorized to charge any fees which may be required, or credit any overpayment to Deposit Account No. 15-0030 A duplicate copy of this sheet is enclosed.	

NOTE: Where an appropriate time limit under 37 CFR 1.494 or 1.495 has not been met, a petition to revive (37 CFR 1.137(a) or (b)) must be filed and granted to restore the application to pending status.

SEND ALL CORRESPONDENCE TO:



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DATE *Dec. 12 2000*

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- 1 -

DESCRIPTION

PHOTON NUMBER STATE GENERATING APPARATUS

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TECHNICAL FIELD

The present invention relates to a device for generating a specified number of photons with known generating time, and more specifically, to a device for generating a specified number of photons in a known schedule. The particularly important specified number is 1,
10 which is able to be used for quantum cryptographic communication.

BACKGROUND ART

In the quantum cryptographic communication system, loading each photon with information enables the detection of an
15 unauthorized listener by the quantum mechanical principle. However, if the same information is loaded on two or more photons, the unauthorized listener may utilize a part of these photons and the presence of the unauthorized listener may not be able to be detected. In this way, ideally, a pulse that contains only one photon at maximum
20 must be used. For this kind of pulse, it is popularly practiced to attenuate the light beam from the laser beam source by an attenuator in such a manner that the mean number μ of photons per pulse becomes about 0.1. By doing this, the probability to contain two or more photons in a pulse can be reduced to 1/100, but the probability to
25 contain one photon in the pulse is also reduced to about 0.1. That is, in case of $\mu=0.1$, transmission is actually carried out only about once per 10 times.

As one example of conventional techniques for improving this kind of process, description will be made on the case stated in the "Key Distribution system and method using Quantum Cryptography" of Japanese Unexamined Patent Publication No. 8-505019 (1996) referring to FIG. 11, which corresponds to FIG. 5 in the embodiment of the said invention. In FIG. 11, numeral 7 denotes a laser that generates pumping light 8 for pumping the nonlinear optical medium 9. In the nonlinear optical crystal 9, a parametric fluorescence pair that causes one photon of the pumping light to stochastically generate two photons is generated. One photon of these (in this case, called the "idler photon 5") is detected by an optical detector and a gate controller 38, and when detected, the gate device 4 is opened to enable the other photon (called the "signal photon 6") to pass. In these conventional techniques, as described in the embodiment of the "Key Distribution system and method using Quantum Cryptography" of Japanese Unexamined Patent Publication No. 8-505019 (1996), for the optical detector, a photo-multiplier tube or a semiconductor avalanche photodiode (hereinafter called "AQ-APD") used under active quenching control was used.

However, if the detector used in the conventional technique is used as a photon detector as it is, when a plurality of photons were incident in a response time of the detector, the detector was unable to detect that a plurality of photons were incident. For example, in AQ-APD, since the amplitude of the pulse becomes constant irrespective of the number of incident photons, it was able to detect that photons were incident but it was unable to obtain the information on the number of incident photons. In addition, when the photo-multiplier tube is used, the quantum efficiency η is as low as about 20 % at maximum, and the

detection efficiency of two photons is extremely low (4 %) because the efficiency is equal to the square of η , and it was unable to detect the incidence of two or more photons.

In the conventional technique, because the use of these
5 detectors was premised, there was no means for judging the number of incident photons.

Consequently, even when a plurality of photons are generated sequentially from a parametric fluorescent pairs within a range of the response time of the detector, the detector opens the gate,
10 causing a problem in that a two-photon-state emerges.

However, on the other hand, it was impossible to generate the "two-photon-state" in which two photons sequentially exist within a range of the response time of the detector.

As described above, because in the conventional technique,
15 the detector was unable to detect the number of incident photons and had no means for judging the number of incident photons, the detector had a drawback in that even if photon pairs were generated sequentially within the response time of the photon detector, it opened the gate and a state in which two or more photons were contained within the response
20 time of the detector was emitted.

Furthermore, in the conventional method, it was unable to accurately generate a plurality of photons in one pulse.

It was also unable to control the timing of photon generation in the pulse.

25 The present invention was achieved to solve these problems, and it is an object of the present invention to provide a device that can suppress uncorrelated two or more photons from being contained in the

response time of the detector, to generate an accurate of correlated photons in one pulse, and to control the timing of photon generation in a pulse.

5

DISCLOSURE OF INVENTION

A photon number state generating apparatus according to the present invention comprises a photon pair source for generating a pair of photons correlated in generating time consisting of a signal photon and an idler photon, a photon number detector for detecting the number of photons of the idler photon, a controller for controlling a gate device in conformity with the information on the number of photons from the photon number detector, and a gate device for controlling an emission of the signal photon.

For a photon pair source for generating a pair of photons, a pumping light source and a nonlinear optical medium on which the pumping light from the pumping light source is incident are provided.

For the nonlinear optical medium on which the pumping light is incident, a nonlinear optical crystal is provided, in which the angle made by the pumping light and the optical axis of the nonlinear optical medium is set to the angle at which tuning curves come in contact with a straight line that corresponds to a specific single wavelength a.

For the nonlinear optical medium on which the pumping light is incident, a nonlinear optical crystal is provided, in which the angle made by the pumping light and the optical axis of the nonlinear optical medium is set to an angle at which the tuning curves come in contact with respective straight lines that corresponds to two specific wavelengths a and b.

In addition, for a nonlinear optical medium on which the pumping light is incident, a waveguide channel type nonlinear optical medium is provided.

Furthermore, for a nonlinear optical medium on which the
5 pumping light is incident, pseudophase matching type nonlinear optical medium is provided.

Still in addition, a pulse height discriminator for discriminating a information on the photon number of a specified range from the photon number detector is provided.

10 In addition, a photon number detector for outputting signals with the output pulse height varied in accordance with the number of incident photons is provided, and for the controller, a pulse height discriminator for discriminating the output pulses with a specified pulse height range from the photon number detector is provided.

15 Furthermore, a pulse height discriminator is provided, in which the information on the photon number from the photon number detector separates the case in which the number of photons that are incident on the photon number detector is one.

Furthermore, a pulse height discriminator for discriminating
20 the height of output pulse from the photon number detector that corresponds to the height when the number of photon incident on the photon number detector is one is provided.

Furthermore, a clock generator and a gate operation frequency judging section for operating the gate device only in a number
25 of times less than a specific number of times within a predetermined time defined by the clock are equipped for the controller.

In addition, a clock generator and a gate operation frequency

judging section for operating the gate device only in response to the first signal from the photon number detector within a predetermined time defined by the clock are equipped for the controller.

In addition, for a gate device for controlling the emission of
5 the signal photon, a plurality of shutters for closing or opening in a time difference shorter than the gate opening or closing time are equipped.

In addition, an optical fiber for allowing the signal photon generated from the photon pair to reach the gate device for controlling the emission of the photon is equipped.

10 In the present invention, of the photon pair comprising a signal photon and idler photon which are generated in the photon sources and correlate with the generated time, by detecting the number of idler photons by a photon number detector, and controlling the gate device in conformity with the information on the number of photons
15 from the photon number detector, the number of photons contained in the signal photon is controlled.

In addition, the pumping light from the pumping light source is allowed to be incident and a photon pair which are generated by the nonlinear optical medium and correlate with the generation time is used
20 as an idler photon and a signal photon.

In addition, in installing the nonlinear optical medium on which the pumping light is incident, the angle made by the pumping light and the optical axis of the nonlinear optical medium is set to an angle in which the tuning curve comes in contact with a straight line
25 that corresponds to a specific single wavelength λ .

In addition, in installing the nonlinear optical medium on which the pumping light is incident, the angle made by the pumping

light and the optical axis of the nonlinear optical medium is set to an angle in which the tuning curve comes in contact with a straight line that corresponds to two specific wavelengths a and b .

In addition, the pumping light is allowed to be incident to the
5 wave guiding channel type nonlinear optical medium.

In addition, the pumping light is allowed to be incident to the pseudo phase matching type nonlinear optical medium.

In addition, the information on the number of photons from the photon number detector which is within a specified range is
10 separated at the pulse height discriminator of the controller.

In addition, the signal from the photon number detector for outputting signals that vary the output pulse height in conformity with the number of incident photons having a specified range of output pulse height is separated by a pulse height discriminator equipped for the
15 controller.

In addition, the information of the number of photons from the photon number detector is separated when the number of photons incident on the photon number detector is one.

In addition, the height of output pulse from the photon
20 number detector which corresponds to the height when the number of photons incident on the photon number detector is one is separated.

In addition, the gate device is operated only in the number of times that is less than a specified number of times within a predetermined time defined by the clock from the clock generator of the
25 controller.

In addition, the gate device is operated only in response to the first signal from the photon number detector within a predetermined

time defined by the clock from the clock generator of the controller.

In addition, a gate device for detecting incidence of idler photons by the photon detector and controlling the emission of signal photons in the number of times less than the specific number of times
5 within a specified time defined by the clock from the clock generator.

The emission of signal photons is controlled by a plurality of shutters that open or close in a shorter time difference than the open or close time.

In addition, the signal photon generated from the photon pair
10 is allowed to reach the gate device that controls emission of the photon by the use of optical fiber.

BRIEF DESCRIPTION OF DRAWINGS

FIG. 1 is a general arrangement drawing of one embodiment
15 according to the present invention;

FIG. 2 is a drawing showing the relationship between the wave length and emission angle of photons generated in the nonlinear optical medium;

FIG. 3 is a drawing showing the relationship between the
20 incident photon (photons) and the output signal of the photon number detector used in one embodiment of the invention;

FIG. 4 is a drawing showing the relationship between the number of incident photons and height of the output signal of the photon number detector used in one embodiment of the invention;

25 FIG. 5 is a general arrangement drawing of one embodiment of the invention;

FIG. 6 is an arrangement drawing of a photon number

detector used in one embodiment of the invention;

FIG. 7 is an arrangement drawing of a gate device used in one embodiment of the invention;

FIG. 8 is an schematic drawing for explaining operation of the gate device used in one embodiment of the invention;

FIG. 9 is a general arrangement drawing of one embodiment of the invention;

FIG. 10 is an schematic drawing for explaining the operation of one embodiment of the invention; and

FIG. 11 is a general arrangement drawing of one example of conventional techniques.

BEST MODE FOR CARRYING OUT THE INVENTION

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EMBODIMENT 1

FIG. 1 is a general arrangement drawing of one embodiment of the invention. In this embodiment, it is a device in which a single photon state is generated and two photons do not densely exist within the resolution time τ of the detector.

20

(Description on Configuration)

In FIG. 1, numeral 1 denotes a photon pair source that generates a photon pair that correlate with the generation time, numeral 2 denotes a photon number detector for detecting an idler photon 5, and numeral 3 denotes a controller for controlling a gate device 4 in response to the information on the number of photons from the photon number detector. The gate device 4 controls the emission of a signal photon 6.

The photon pair source 1 comprises a nonlinear optical medium 9 and a pumping light source 7 of a pumping light 8 that pumps the nonlinear optical medium. The idler photon 5 generated in the nonlinear optical medium 9 is converged to the photon number detector 2 via a filter 17
5 that allows the object idler photon to selectively penetrate by a lens 15. From the photon number detector 2, pulses of different height are outputted in accordance with the number of photons incident in one time. Only when the pulse height is that when the number of incident photon is one photon, the pulse height discriminator 12 triggers the gate
10 device controller 13, and the trigger causes the gate device controller 13 to open the gate device 4 for a predetermined time.

On the other hand, the signal photon 6 is focused by the lens 15, and is converged into an optical fiber 10 while passing a filter 16 for selectively penetrating 2 λ -wavelength photons of a signal light.
15 Numeral 14 is an fine alignment device for allowing the light from the outside to be efficiently incident on the optical fiber. The optical fiber 10 is used to delay the signal photon 6 to reach the gate device 4 for the time required from the incidence of the idler photon 5 on the detector to the start of control of the gate device 4 in the procedure as described
20 above.

(Description on photon pair generator)

In the nonlinear optical medium 9, the idler photon 5 and the signal photon 6 that have wavelength 2 λ double the wavelength λ of
25 pumping light 8 are generated by down conversion. In this embodiment, argon laser that has 351.1 nm wavelength is used for the pumping light source 7. In this event, the idler photon 5 and the signal photon 6 are

generated as a pair, the sum of whose energies generated is equal to the energy of the photon of 351.1 nm wavelength, that is, a photon of 702.2 nm wavelength, respectively.

As described in detail in the Japanese Patent Application No. 9-353078 (1997) "Photon Beam Generator," setting the optical axis of the nonlinear optical medium to a specific angle with respect to the pumping light enables the idler photon 5 and signal photon 6 to be generated in a form of beam as well as in a high efficiency. FIG. 2 shows a tuning curve when the optical axis of β -Barium-Boron-Oxide (BBO) crystal is set to the angle of 50.4° with respect to the pumping light. In FIG. 2, the wavelength of the photon generated is taken as abscissa and the emitting direction of the photon with respect to the incident direction of the pumping light is taken as ordinate. As seen in the figure, two tuning curves come in contact with a straight line that corresponds to the 702.2 nm wavelength. Under this condition, a 702.2-nm wavelength fluorescent pair are emitted in a form of beam in directions of plus 3° and minus 3°, respectively. By using this kind of nonlinear optical medium, a photon pair is generated efficiently with respect to the incident power of the pumping light, and as a result, in case the single photon is generated at an equivalent rate, it is possible to suppress the power consumption of the equipment to a low level.

In this case, a parametric fluorescent pair was used as a method for generating a photon pair that correlates with the generating time, but needless to say, it is possible to generate a photon pair by any other methods. For example, it is possible to use a cascade emission process from the excited state, etc.

(Description on Photon Number Detector)

In this embodiment, a Visual Light Photon Counter (hereinafter called VLPC) developed by Boeing is used as a photon number detector. This VLPC is able to detect how many photons are incident at a high quantum efficiency as described in detail in the paper titled "Multi-photon Counting using Visible Light Photon Counter" by Jungsang Kim, Shigeki Takeuchi, Yoshihisa Yamamoto, and Henry H. Hogue published in the February 15, 1999 issue of Applied Physics Letters.

Referring now to FIG. 3, the operation when a plurality of photons are incident on the detector is explained. In FIG. 3, the abscissa is the time and the ordinate the height (pulse height) of output pulse from VLPC. The graph also shows the output pulse (a) when only one photon is incident, (b) when two photons are incident simultaneously, (c) two photons are incident at intervals of 3 ns, and (d) two photons are incident at intervals of 5 ns, respectively, from top to bottom. As described above, when two photons are incident simultaneously, the pulse height becomes about double that when one photon is incident.

FIG. 4 shows the results of investigating the distributions of pulse height when the number of photons incident on the detector is one photon and when it is two photons, respectively. The two-photon incidence was carried out using a parametric fluorescent pair, but since there is a problem of optical adjustment, both photons of the photon pair are not always able to be incident on VLPC for all of the photon pairs generated. In the graph, the portion of 10 mV or less is noise, and the peak centered around 37 mV corresponds to the one-photon detection

and the peak centered around 74 mV corresponds to the two photon detection. By the way, VLPC outputs detection pulses of a height nearly proportional to the number of photons because of its structure, when two or more photons are incident.

5 (Specific Configuration and Description of Controller)

The assessment with optical adjustment problems, etc. corrected indicates that the probability to judge "one photon" in spite of the two-photon incidence was about 35 % when the quantum efficiency to one-photon incidence of a photon number detector using VLPC is
10 75 % when only the range from 10 mV to 56 mV of the pulse height from the detector is judged "one-photon detection." In the pulse height discriminator 12, the gate device controller is triggered only when this kind of signals of pulse height are input from the photon number detector using a pulse height analyzer. In response to the triggering
15 operation, the gate device is opened or closed. The time in which the gate device is open is desirably the resolution time of the detector, and preferably between 2 ns and 5 ns in the present embodiment.

The probability of misjudging the two photons as one photon can be further improved by improving the quantum efficiency of the
20 photon number detector using VLPC. In this kind of detector, as stated in "High Quantum-efficiency Single-photon Counting System" by Shigeki Takeuchi, Jungsang Kim, Yoshihisa Yamamoto, and Henry H. Hogue published in the February 22, 1999 issue of Applied Physics Letters, the quantum efficiency is able to be improved nearly to 90 %, and in such a case, the probability to misjudging two photons as one
25 photon can be suppressed to 18 % or less.

By using this kind of detector, the phenomenon in that "a

plurality of photons are generated sequentially from a parametric fluorescent pair within around response time of the detector, open the gate and the two-photon-state is emitted" in the conventional technique was able to be reduced to one fifth or less. In addition, because in the
5 conventional technique, in order to avoid two-photon emission, the average number of photons per one pulse was made small (for example, 0.1), when this technique was adopted to communication, the transmission efficiency was reduced to the same ratio, but according to the present embodiment, an average of one photon is able to be emitted
10 per one pulse, and the transmission efficiency is able to be improved.

EMBODIMENT 2

In Embodiment 1, the wavelength of signal beam generated was 702.2 nm, but needless to say, this wavelength is able to optionally
15 changed by selecting a suitable pumping light source laser and nonlinear optical medium. For example, it is naturally possible to generate wavelengths in the vicinity of 1550 nm, vicinity of 1310 nm, and in the vicinity of 800 nm, which are generally adopted to communication using optical fiber.

20 The method for generating a photon pair shown in Embodiment 1 (FIG. 2) is a method suited to obtain a photon pair beam with equal wavelengths and small angular dispersion, but it is possible to obtain a photon pair with different wavelengths by changing the optical axis direction of the BBO crystal for other object of use. In such
25 event, the two tuning curves of FIG. 2 come in contact with straight lines that correspond to different wavelengths, respectively. In such event as well, the photons are taken out at an angle in which the tuning curves

shown in FIG. 2 come in contact with the straight lines that correspond to the relevant wavelengths. According to this condition, photons that generally disperse in a form of cone are converged into one beam and the photon beam with high distribution density is able to be obtained.

5 For other embodiments of the invention, there is a device for generating the 532-nm pumping light 8 using an up-conversion laser of a semiconductor excited Yag laser as a pumping light source 7 in FIG. 1, and generating a 1310-nm photon as a signal photon 6 and a 896-nm photon as an idler photon 5. In such event, by the method described in
10 detail in the Japanese Patent Application No. 9-353078 (1997) "Photon Beam Generator," the angle made by the optical axis of the nonlinear optical medium is set to such an angle that the tuning curve comes in contact at 1310 nm and 896 nm, respectively, in order to improve the photon pair generating efficiency. In addition, by setting the
15 wavelength of the idler photon to a near infrared area close to the wavelength of visible light, the number of photons is able to be detected with the quantum efficiency of the photon number detector 2 set to a high level.

With this kind of configuration, it is able to generate photons
20 in the vicinity of 1310 nm with a small transmission loss in the optical fiber in such a manner as to prevent two photons within the resolution time τ of the detector from existing densely. In the present embodiment, it becomes possible to efficiently generate the photon pair by establishing the crystal angles as described above, and it becomes also
25 possible to maintain the high detection efficiency of the number of idler photons, and as a result, the power consumption of the device is able to be reduced.

EMBODIMENT 3

FIG. 5 shows another embodiment of the invention. In this embodiment, numeral 7 is a pumping light source, numeral 18 an optical fiber for guiding the pumping light, numeral 19 a waveguide channel type nonlinear medium, numeral 20 a waveguide channel type filter for discriminating the fluorescent pair and pumping lights generated from the waveguide channel type nonlinear optical medium 19, numeral 21 an emission port of pumping light, and numeral 22 a waveguide channel type filter for dividing the fluorescent pair into two branches.

In this embodiment, the parametric fluorescent pair is generated in the waveguide channel type nonlinear optical medium 19. The fluorescent pair has vertical and horizontal polarized lights, respectively, and in the waveguide type filter 22 that operates as a polarizing beam splitter, that with one of the polarized light pair is transmitted to the photon number detector 2 and another to the optical fiber 10.

By this kind of configuration, it becomes possible to downsize the device, and optical alignment is no longer required.

In this kind of embodiment, as the nonlinear optical medium, a waveguide channel type nonlinear optical medium 19 is used. As described by "two photon correlation phenomenon by optical waveguide channel type nonlinear type element" written by Sanaka et al. in Page 321, the second separate volume, No. 2, Volume 53 of the Proceedings of the Japanese Society of Physics, in the pseudo phase matching type waveguide channel nonlinear medium, a nonlinearity that can satisfy a conditions in which the pumping light used and the photons generated

are generated in parallel can be obtained by pseudo phase matching.

With this, wavelengths of pumping light and generated photon are able to optionally chosen.

EMBODIMENT 4

5 For other embodiment of the invention, FIG. 6 shows a case when a photon number detector in Embodiment 1 shown in FIG. 3 and 4 is configured by combining a plurality of photon detectors. In FIG. 6, numerals 23, 24, and 25 are waveguide channel type beam splitters with
10 a split ratio of 50:50, and numerals 26 through 29 are photon detectors. For the photon detectors 26 through 29, detectors that can detect incidence of photons but are unable to distinguish the incident photon number may be used. For example, SPCM (Single Photon Counting Module)-AQ commercially available from Seiko EG&G which drives the
15 incident photon number avalanche photo-diode by a Geiger mode may be used.

The photon that is propagated through optical fibers are incident on photon detectors 26 through 29 at a probability of one in four, respectively, while it passes through beam splitters 23 through 25.
20 Consequently, for example, when two photons are incident within the response time of the detectors, two detectors respond at the probability of three in four and can distinguish them as two photons.

The detection signals from detectors 26 through 29 may be transmitted to the pulse height discriminator 12 of FIG. 3 as parallel
25 signals as they are or may be compressed in a suitable form and transmitted as serial signals. In addition, it is also possible to integrate the photon number detector with the pulse height discriminator 12 by

incorporating a logic circuit at the subsequent stage of each detector.

In the present embodiment, for one example, a case to use four detectors in parallel was shown, but an optional number of detectors may be used. In general, when N pieces of detectors are used
5 in parallel and beam splitters are installed in such a manner that photons are incident on these detectors at an equal probability, the detection probability of two photon incidence is given by $(N-1)/N$.

In the present embodiment, for beam splitters 23 through 25, 50:50 beam splitters are used, but beam splitters of suitable split ratio
10 may be used in accordance with the quantum efficiency, etc. of each detector.

As a method for receiving photons with a plurality of detectors installed in parallel, a method for using a beam splitter to divide the light path into a plurality of light paths is adopted, but for
15 example, when the beam receiving surfaces are able to be installed adjacent to each other, lenses, etc. may be used to enable a plurality of these photon detectors to detect photons at a uniform detection ratio, respectively.

20

EMBODIMENT 5

For still another embodiment of the invention, in the pulse height discriminator 12 of FIG. 1, it is possible to cut out the component only that corresponds to the case when two photons are incident from the detection signals from the photon number detector. In such event,
25 from the gate, the state in which two photons are contained within the response time of the detector is emitted. Needless to say, it is possible to cut out optional combinations such as the state of N photons or the

state of even number of photons in the similar manner.

EMBODIMENT 6

For yet another embodiment of the invention, FIG. 7 shows
5 the case in which two shutters are equipped for the gate device 4 of FIG.
1. In FIG. 7, numeral 10 denotes an optical fiber for delaying the signal
photon in the reaching time to the gate device, numerals 30, 31 denote
electro-optic elements, numerals 32, 33, 34 denote polarizing plates,
numeral 35 denotes a NOT gate, numeral 36 denotes a delay device, and
10 numeral 13 denotes a controller. In this event, polarizing plates 33 and
34 are set in such a manner that they have the maximum transparency
for the polarization of the light that has passed the polarizing plate 32
and do not transmit the light which has polarization crossing at right
angles to said light. In addition, the electro-optic elements 30, 31
15 rotate the polarization angle by 90° when the logic of the control signal is
1 and does not rotate the polarization when the logic is 0.

The gate device preferably holds the gate open condition only
while the photon is present, and is closed during other periods.
However, with a single electro-optic element, the gate time was unable to
20 be set to the time less than that specified by the repetitive response time
of the electro-optic element. The present embodiment has achieved the
gate operation shorter than the repetitive response time of the shutter by
installing two shutters.

Referring now to FIG. 8, operation of the gate circuit is
25 described. In FIG. 8, time is plotted in abscissa. The graph at the top
indicates the probability in which the desired photon number state
reaches the gate operating section, Graph A the signal at point A of FIG.

7, and Graph B the state of signal at point B of FIG. 7 in the similar manner. Denotation A may be considered as the control signal itself from the controller. The electro-optical element 31 transmits the photon when the logic 0 is entered and shields the photon when the logic
5 1 is entered in combinations with polarization rotators 33, 34.

The electro-optic element 30 operates in the same way in combinations with polarizers 32, 33.

As in the state at time T0 of graph A of FIG. 8, the control signal from the controller is usually set 1. In this case, the gate device
10 does not transmit the photon by the electro-optical element 31. In this event, to the electro-optical element 30, logic 0 is entered by the NOT gate 35, and photon is allowed to be transmitted.

The controller 13 changes the output logic from 1 to 0 so that the electro-optic element 31 opens at the time T1 right before the time
15 when the photon is expected to reach the gate operating section. In this event, by the operation of the delay unit 36, the electro-optical element 30 is kept to logic 0. In such event, the photon is ready to penetrate the gate device. This state continues for the time set by the delay unit. After the delay, at T2, the logic to the electro-optic element flips to 1 and
20 the photon is unable to penetrate the portion of electro-optic element 30. At time T3, the control signal again changes from 0 to 1, causing the electro-optic element 31 to change to closed state, and at T4, it returns to initial state.

By the above-mentioned configuration, it is possible to open
25 the gate device only for the time shorter than the response time of individual electro-optic element, rendering itself capable for selectively emitting the required photons only.

EMBODIMENT 7

FIG. 9 shows further embodiment of the invention. In FIG. 9, numeral 37 is a clock generator for generating a clock signal supplied to the controller. Referring now to FIG. 10, the operation of this
5 embodiment will be described. In FIG. 10, the time is plotted in abscissa. Graph C is a clock signal observed at point C of FIG. 9, Graph D is signal from the photon number detector 12 observed at point D of FIG. 9, Graph E is a gate control signal from the controller 13, and Graph F is the photon distribution observed in the optical fiber 11 after
10 photon passed the gate device 4.

As seen in Graph D, from the photon number detector 2, signals with pulse height corresponding to the number of incident photons at that time are constantly outputted. The pulse height discriminator 12 chooses the pulse height corresponding to the photon
15 incidence of one at a time. In the controller 13, the gate device 4 is opened only against the signal from the pulse height discriminator which is first entered after the clock rise-up (Graph E). As a result, from the optical fiber 11, a single photon is emitted at nearly uniform intervals as seen in Graph F.

20 In this embodiment, the pulse height discriminator 12 chooses only the state in which only one photon is present within the response time of the photon number detector 2, but needless to say, it is possible to choose a state corresponding to two or more photons. By this, it becomes possible to generate a multiple photon number state at
25 intervals close to uniform intervals. If the number of generated photon pairs is increased, the intervals are able to be further brought to uniform intervals.

EMBODIMENT 8

In Embodiment 7, the gate device was opened only once within specified time intervals, but may be opened N times within the specified time intervals. By doing this, it is possible to create a state in which N photons are contained within a specified time. Even in such a case, it becomes possible to create a state in which N photons are repeatedly generated more uniform intervals by increasing the number of generated photon pairs.

As described above, in the photon number state generating apparatus according to the present invention, an optional photon number state is able to be generated irrespective of the response speed of the detector by equipping a photon pair source for generating photon pairs that correlate with the generating time, photon number detector for detecting one photon of the pair, and a controller for controlling the gate device in conformity with the information of the number of photons from the photon number detector.

It is also possible to efficiently generate an optional photon number state by equipping a pumping light source and a nonlinear optical medium on which the pumping light is incident from the pumping light source, as a photon pair source.

It is still possible to efficiently generate the photon number state by properly adjusting the nonlinear optical element.

It is also possible to eliminate optical alignment and achieve easy handling by equipping the waveguide channel type nonlinear optical medium for the nonlinear optical medium.

In addition, it is possible to generate a photon number state at specified time intervals by equipping, for the controller, a clock

generator and a gate operating frequency judging section for operating the gate only in the number of times less than the specific number of times within a predetermined time defined by the clock.

Furthermore, it is possible to achieve a gate at a time
5 extremely shorter than the repetitive frequency of the shutter itself by equipping, for the gate device, a plurality of shutters that open or close at a time difference shorter than the gate open or close time.

INDUSTRIAL APPLICABILITY

10 A photon number state generating apparatus according to the present invention is able to generate an optional photon number state irrespective of the response speed of the detector by equipping a photon pair source for generating a photon pair that correlated with the generating time, photon number detectors for detecting one photon of
15 the photon pair, and a controller for controlling the gate device in conformity with the information of the number of photons from the photon number detector, and it is useful as an apparatus for generating a specified number of photons whose generating time is known.

CLAIMS

1 1. A photon number state generating apparatus
2 comprising:

3 a photon pair source for generating a pair of photons
4 consisting of a signal photon and an idler photon which are corrected in
5 time of generation each other;

6 a photon number detector for detecting a number of the idler
7 photons;

8 a gate device for controlling an emission of the signal
9 photons;

10 a controller for controlling the gate device in response to a
11 photon number information from the photon number detector.

1 2. The photon number state generating apparatus of claim
2 1, wherein said photon pair source comprises:

3 a pumping light source;

4 a nonlinear optical medium on which a pumping light from
5 the pumping light source is incident.

1 3. The photon number state generating apparatus of claim
2 2 comprising:

3 a nonlinear optical crystal in which an angle between the
4 pumping light and an optical axis of the nonlinear optical medium is set
5 to an angle at which tuning curves come in contact with a straight line
6 corresponding to a single specific wavelength λ .

1 4. The photon number state generating apparatus of claim
2 2 comprising:

3 a nonlinear optical crystal in which an angle between the
4 pumping light and an optical axis of the nonlinear optical medium is set
5 to an angle at which tuning curves come in contact with two straight
6 lines corresponding to two specific wavelengths a and b.

1 5. The photon number state generating apparatus of claim
2 2, wherein said nonlinear optical medium on which the pumping light is
3 incident comprises a waveguide channel type nonlinear optical medium.

1 6. The photon number state generating apparatus of claim
2 2, wherein the nonlinear optical medium on which the pumping light is
3 incident comprises a pseudophase matching type nonlinear optical
4 medium.

1 7. The photon number state generating apparatus of claim
2 1 comprising:

3 a pulse height discriminator equipped in the controller for
4 discriminating a photon number information having photon number
5 within a specified range, wherein the controller controls the gate device
6 in response to the photon number information from the photon number
7 detector.

1 8. The photon number state generating apparatus of claim
2 1 comprising:

3 a photon number detector in which an output pulse height

4 changes in response to the number of incident photons;
5 a pulse height discriminator equipped in the controller for
6 discriminating output pulse of photon number detector having a pulse
7 height of a specified range.

1 9. The photon number state generating apparatus of claim
2 1 comprising:
3 a discriminator for discriminating a case in which a number
4 of photon incident on the photon number detector in one.

1 10. The photon number state generating apparatus of claim
2 1 comprising:
3 a pulse height discriminator for discriminating a case in
4 which an output pulse height of the photon number detector
5 corresponding to a number of incident photon that is one.

1 11. The photon number state generating apparatus of claim
2 7, wherein said controller comprises:
3 a clock generator;
4 a gate operation frequency judging section for controlling the
5 gate device to be opened or closed for less than a specified number of
6 times within a predetermined time defined by clock signal of the clock
7 generator.

1 12. The photon number state generating apparatus of claim
2 7, wherein said controller comprises:
3 a clock generator;

4 a gate operation frequency judging section for controlling the
5 gate to be opened or closed only for a first signal of the photon number
6 detector within a predetermined time defined by clock signal of the clock
7 generator.

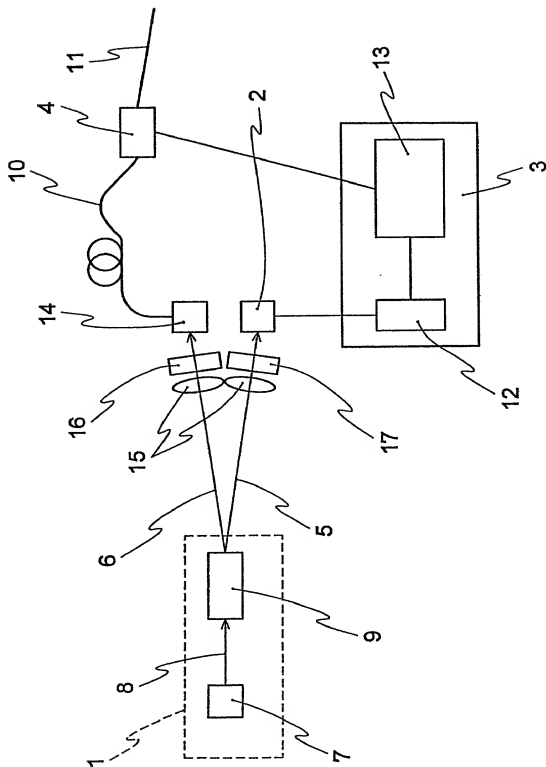
1 13. The photon number state generating apparatus of claim
2 1, wherein said gate device for controlling an emission of the signal
3 photon comprises a plurality of shutters which open or close in a time
4 difference shorter than a open or close time of the shutters.

1 14. The photon number state generating apparatus of claim
2 1 further comprising:
3 an optical fiber for allowing the idler photon to reach the gate
4 device for controlling an emission of the photon.

ABSTRACT

An apparatus for generating a specified number of photons whose generating time is known, and further an apparatus for
5 generating a specified number of photons in the known schedule are provided. The particularly important specified number is 1 and it is able to be applied to quantum cryptographic communication. The apparatus comprises a photon pair source for generating a photon pair that comprises a signal photon and an idler photon and correlates with
10 the generating time, photon number detectors for detecting the photon number of idler photons, a controller for controlling the gate device in conformity with the information on the photon number from the photon number detector, and a gate device for controlling the emission of the signal photon.

FIG. 1



200351US2PCT

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FIG. 2

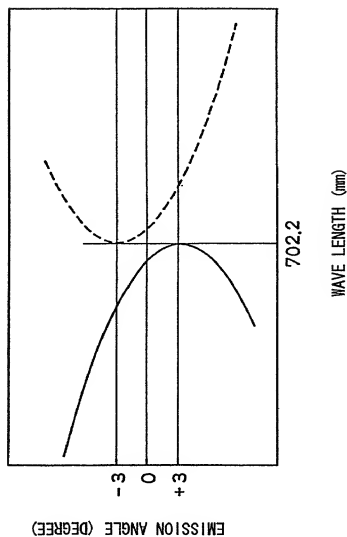


FIG. 3

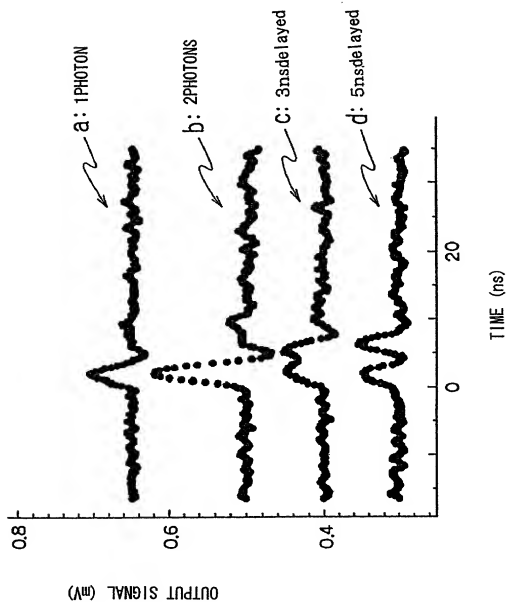
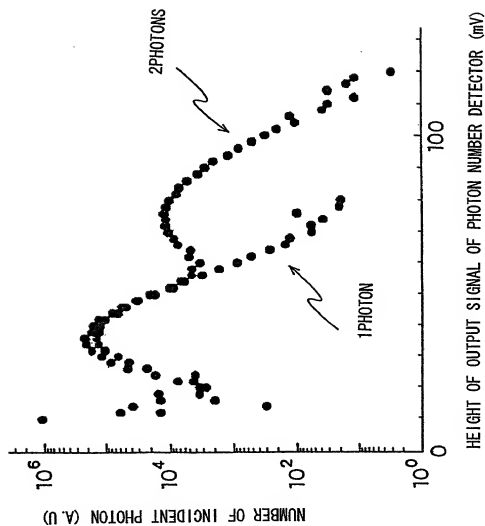
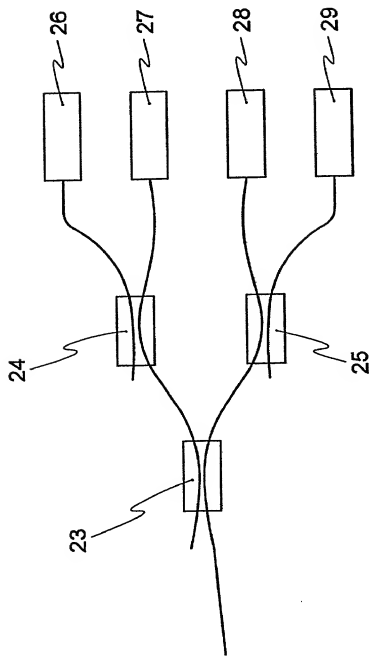


FIG. 4



The diagram shows a system architecture. A sensor (7) is connected to a processing unit (18). The processing unit (18) is connected to a control unit (20). The control unit (20) is connected to a sensor (22). The sensor (22) is connected to a control unit (2). The control unit (2) is connected to a control unit (12). The control unit (12) is connected to a control unit (13). The control unit (13) is connected to a control unit (10). The control unit (10) is connected to a control unit (11).

FIG. 6



09/719150

FIG. 7

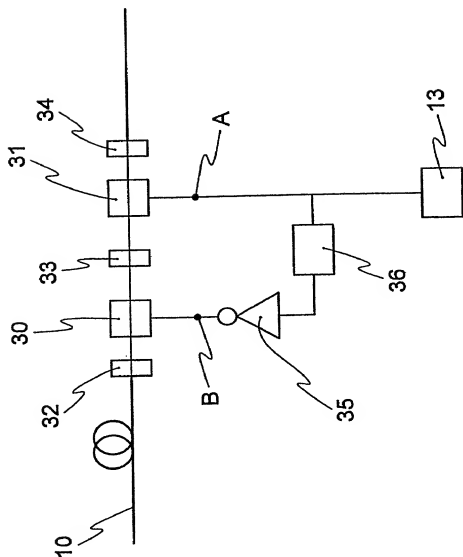


FIG. 8

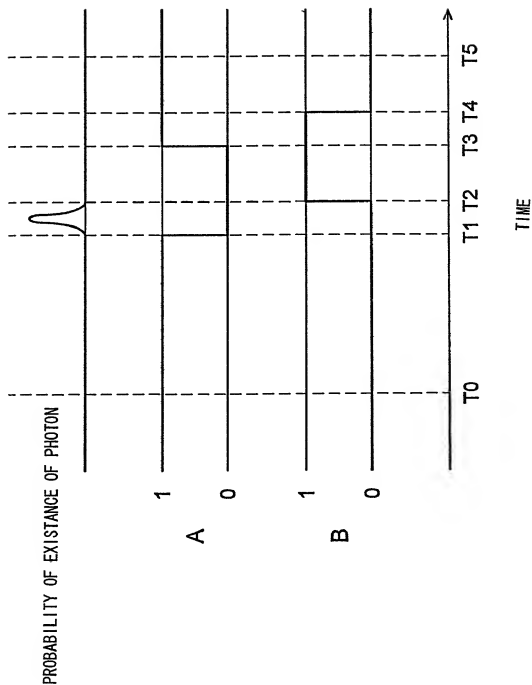


FIG. 9

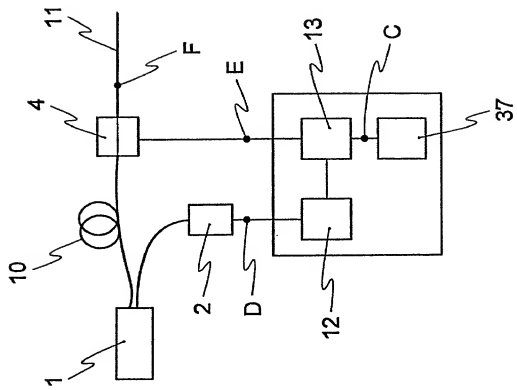


FIG. 10

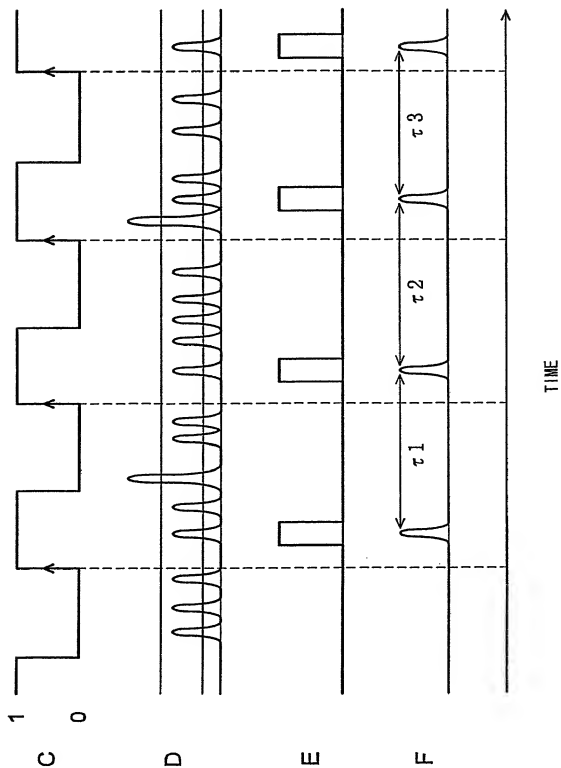
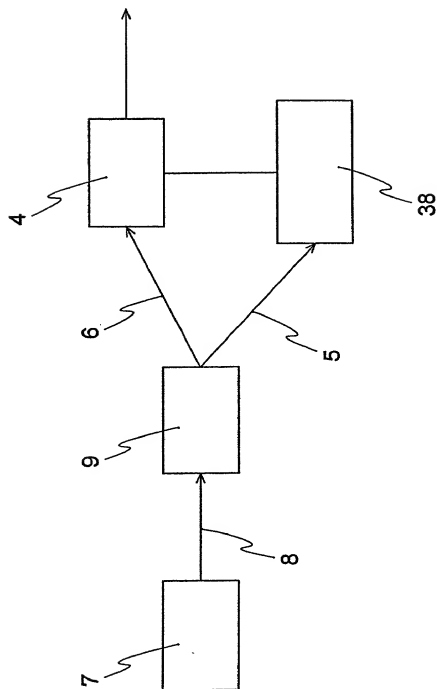


FIG. 11



Declaration and Power of Attorney For Patent Application

特許出願宣言書及び委任状

Japanese Language Declaration

日本語宣言書

下記の氏名の発明者として、私は以下の通り宣言します。

As a below named inventor, I hereby declare that:

私の住所、私書箱、国籍は下記の私の氏名の後に記載された通りです。

My residence, post office address and citizenship are as stated next to my name.

下記の名称の発明に関して請求範囲に記載され、特許出願している発明内容について、私が最初かつ唯一の発明者（下記の氏名が一つの場合）もしくは最初かつ共同発明者（下記の名称が複数の場合）であると信じています。

I believe I am the original, first and sole inventor (if only one name is listed below) or an original, first and joint inventor (if plural names are listed below) of the subject matter which is claimed and for which a patent is sought on the invention entitled.

PHOTON NUMBER STATE GENERATING

APPARATUS

上記発明の明細書は、

- ☐ 本書に添付されています。
☐ ____月____日に提出され、米国出願番号または特許協定条約国際出願番号を____とし、
(該当する場合) ____に訂正されました。

the specification of which

- ☐ is attached hereto.

☒ was filed on November 10, 1999

as United States Application Number or
PCT International Application Number

ECT/JP99/06244 and was amended on
____ (if applicable).

私は、特許請求範囲を含む上記訂正後の明細書を検討し、内容を理解していることをここに表明します。

I hereby state that I have reviewed and understand the contents of the above identified specification, including the claims, as amended by any amendment referred to above.

私は、連邦規則法典第37編第1条56項に定義されるとおり、特許資格の有無について重要な情報を開示する義務があることを認めます。

I acknowledge the duty to disclose information which is material to patentability as defined in Title 37, Code of Federal Regulations, Section 1.56.

Japanese Language Declaration
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私は、米国法典第35編119条 (a) - (d) 項又は365条 (b) 項に基づき下記の、米国以外の国の少なくとも一カ国を指定している特許協力条約365 (a) 項に基づく国際出願、又は外国での特許出願もしくは発明者証の出願についての外国優先権をここに主張するとともに、優先権を主張している、本出願の前に出願された特許または発明者証の外国出願を以下に、枠内をマークすることで、示しています。

Prior Foreign Application(s)

外国での先行出願

104600/1999

(Number)
(番号)

Japan

(Country)
(国名)

(Number)
(番号)

(Country)
(国名)

私は、第35編米国法典119条 (e) 項に基づいて下記の米国特許出願規定に記載された権利をここに主張いたします。

(Application No.)
(出願番号)

(Filing Date)
(出願日)

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(Filing Date)
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I hereby claim foreign priority under Title 35, United States Code, Section 119 (a)-(d) or 365(b) of any foreign application(s) for patent or inventor's certificate, or Section 365(a) of any PCT International application which designated at least one country other than the United States, listed below and have also identified below, by checking the box, any foreign application for patent or inventor's certificate, or PCT International application having a filing date before that of the application on which priority is claimed.

Priority Claimed
優先権主張

<input checked="" type="checkbox"/>	<input type="checkbox"/>
Yes	No
はい	いいえ
<input type="checkbox"/>	<input type="checkbox"/>
Yes	No
はい	いいえ

12/4/1999

(Day/Month/Year Filed)
(出願年月日)

(Day/Month/Year Filed)
(出願年月日)

I hereby claim the benefit under Title 35, United States Code, Section 119(e) of any United States provisional application(s) listed below.

(Application No.)
(出願番号)

(Filing Date)
(出願日)

I hereby claim the benefit under Title 35, United States Code, Section 120 of any United States application(s), or Section 365(c) of any PCT International application designating the United States, listed below and, insofar as the subject matter of each of the claims of this application is not disclosed in the prior United States or PCT International application in the manner provided by the first paragraph of Title 35, United States Code Section 112, I acknowledge the duty to disclose information which is material to patentability as defined in Title 37, Code of Federal Regulations, Section 1.56 which became available between the filing date of the prior application and the national or PCT International filing date of application.

(Status: Patented, Pending, Abandoned)
(現況: 特許許可済、係属中、放棄済)

(Status: Patented, Pending, Abandoned)
(現況: 特許許可済、係属中、放棄済)

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

Japanese Language Declaration

(日本語宣言書)

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(弁護士、または代理人の指名及び登録番号を明記のこと)

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(Supply similar information and signature for third and subsequent joint inventors.)